

USE OF BOTTOM ASH AND FLY ASH IN RAMMED-EARTH CONSTRUCTION

Final Report

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USE OF BOTTOM ASH AND FLY ASH IN RAMMED-EARTH CONSTRUCTION

EXECUTIVE SUMMARY

Rammed-earth (RE) construction is an historical method using earth compressed into a form similar to adobe. RE is typically associated with buildings in the southwestern United States, but RE construction has been demonstrated and/or used throughout the eastern United States, the Midwest, and in North Dakota. Some soils are appropriate for RE construction without the use of additives as stabilizers; however, additives are frequently used to add strength and durability to RE and adobe. A demonstration of RE construction in North Dakota was proposed to utilize North Dakota lignite bottom ash and fly ash as additives to produce an improved soil for RE construction. It was proposed that bottom ash could be used to enhance the insulative properties of the RE walls and that fly ash could be used to enhance their strength and durability. Portland cement and lime are frequently used as additives for this purpose.

With funding from the North Dakota Industrial Commission (authorized by the Lignite Research Council) and the U.S. Department of Energy, the Energy & Environmental Research Center (EERC) performed an investigation to evaluate the potential for use of North Dakota bottom ash and fly ash in RE construction. The issues related to the proposed demonstration of RE technology in North Dakota included:

1. Appropriateness of the local soils.
2. The use of coal combustion bottom ash and fly ash and other additives such as portland cement.
3. The performance of RE in the North Dakota climate.

The EERC performed several tasks focusing on the engineering and physical performance of RE produced using North Dakota soil, bottom ash, and fly ash. The procedures used are applicable to materials from any location.

An initial test matrix of RE mixes incorporating soil, bottom ash, fly ash, and cement was developed, and specimens were prepared and tested for strength development. Strength was the preliminary criterion used to evaluate the potential engineering performance of the RE specimens and identify mixes for further evaluation. Strengths of 200 to 300 psi are recommended in the New Mexico Adobe and Rammed-Earth Building Code (See Appendix A), and a summary of building codes for earth construction (McHenry, 1984) also indicates the desirable level of strength from 90 psi (uncured RE) to 300 psi (cured RE). Based on this information, it was decided to use these levels of strength as a guideline in selecting a limited number of mixes for additional testing. Strength development was the lowest in soil only and soil–bottom ash mixes. The addition of fly ash and cement increased the strength development.

Based on these preliminary strength development tests, six mixes and a control soil sample were identified for further durability testing. One mix selected incorporated only soil and bottom

ash, although the strength of this mixture did not meet the recommended strengths. The soil–bottom ash mixture was included because it had been hypothesized that bottom ash could be used to improve the insulative properties of the soil. It was important to evaluate the engineering performance of that mix in addition to evaluating the impact of bottom ash on the R-value. Additional specimens were prepared and tested using standard durability tests. Two of the selected mixes exceeded 300 psi. Three of the selected mixes exceeded the recommendation for strength for uncured RE (90 psi). Those mixes that exceeded 300 psi both included cement in the mix.

TABLE ES-1

Strength of Selected Mixes after 7 Days of Curing	
Mix Design	7-day Strength, psi
1: 100% soil	52
4: 70% soil and 30% bottom ash	50
8: 80% soil and 20% fly ash	107
11: 80% Base 1 (70% soil and 30% bottom ash) and 20% fly ash	123
13: 80% Base 1, 10% fly ash, and 10% cement	788
14: 90% Base 1 and 10% fly ash	100
16: 90% Base 1, 5% fly ash, and 5% cement	462

Mixes that incorporated either fly ash or fly and cement performed better than the soil control sample and the soil–bottom ash mix. Additional durability tests also indicated improved performance by the mixes with fly ash and fly ash–cement additions over the soil and soil–bottom ash. The mixes with cement performed the best on all strength and durability tests performed. Scanning electron microscopy was used to examine the level of cementation between particles. The micrographs supported the durability testing by providing a visual verification of cementitious growths between particles in the samples with cementitious material and virtually no evidence of cementation in the soil–bottom ash sample.

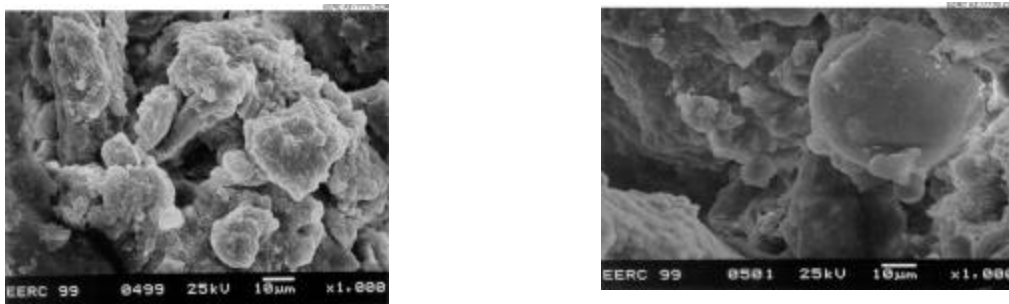


Figure ES-1. Comparison of bottom ash–soil and fly ash–soil SEMs supporting durability tests. Mix 4 (left) shows discrete particles in the bottom ash–soil sample, while Mix 14 (right) shows cementitious development with few voids.

The use of bottom ash was proposed for RE, with the hypothesis that the bottom ash would provide an improved insulation for RE walls. The EERC tested RE specimens with and without bottom ash to determine if the bottom ash provides added insulation. R-values for these comparative specimens indicate a 14% increase in the R-value when 15% bottom ash is added to the mix. While the R-values are low compared to traditional insulation, it is generally agreed that the heat capacity of earthen walls would partially offset the low R-value.

Environmental performance testing was also performed on all proposed RE components. The environmental performance tests included a comparative evaluation of radon emanation, total elemental composition, and leaching characterization. The leaching characterization was performed on both the proposed components and the three recommended RE mixes. Results of the environmental performance evaluations indicated that all components were environmentally safe to use in RE. Only the soil provided a measurable level of radon emanation. While the test results cannot be directly related to radon emanation in a RE building, it is important to note that the proposed additives did not emanate any measurable radon, making them good candidates for RE construction.

The results of the evaluation of mix designs, strength development, durability, and environmental performance indicate that RE construction is technically feasible using the North Dakota components tested. Further, based on previous EERC studies, it is anticipated that other North Dakota bottom ash and fly ash materials will also perform similarly. Evaluations similar to the ones performed in this effort would be required for other soil-additive mixtures because the performance of soils varies widely.

The EERC also performed a limited evaluation of the logistical and economic feasibility of RE construction in North Dakota. The technology proposed for the RE construction demonstration in North Dakota was determined to be practical and addresses issues of water contacting the RE walls. This technology offers no advantages specific to North Dakota or the coal combustion byproducts proposed for use in RE, but should be useful in RE construction in any location. RE construction using either the proposed technology or other published techniques is labor-intensive. The EERC sees the lack of experienced RE construction laborers as one factor that may impede the success of RE in North Dakota. Historical records indicate only limited numbers of RE homes in North Dakota and even throughout the United States, so the EERC sees limited potential for RE to be widely used in North Dakota.

The EERC concludes that the use of lignite fly ash and bottom ash in RE construction is technically feasible and environmentally safe. The proposed North Dakota soil does require an additive to produce a durable RE, and cement, cementitious fly ash, or combinations of these provide improved durability. Addition of bottom ash improved the insulation properties of RE specimens tested, and the EERC recommends the addition of bottom ash at 10%–30% for the soil included in this study. Results indicated favorable engineering and environmental performance of lignite fly ash and bottom ash in RE, but the limited potential for RE use in North Dakota and the relatively low addition rates of lignite fly ash and bottom ash indicate that RE construction would be a low-volume use application for North Dakota lignite ash.

USE OF BOTTOM ASH AND FLY ASH IN RAMMED-EARTH CONSTRUCTION

INTRODUCTION

Earth architecture is found around the world, ranging from extremely simple structures to elaborate and luxurious buildings. Adobe and rammed earth (RE) are common earth building technologies and have generally been developed through trial and error. Both use readily available material and earth and are labor-intensive construction techniques. In the United States, earth building had wide popularity until World War II. During the 1930s, the U.S. Department of Agriculture researched and demonstrated earth building. With cultural and economic changes in the United States following World War II, efforts in the area of earth building decreased, and the construction skills required for adobe and RE construction, common before that time, were largely lost. However, earth architecture and building technology is regaining popularity, primarily in the southwestern United States. In a brief overview of earth building technologies and trends, it was noted that modern earth buildings tend to be higher-cost homes because of the labor involved. An Internet search indicates that some earth homes are built by the owners to limit labor costs. In the southwestern United States, there are builders who specialize in earth buildings, but they appear to be few. The literature and Internet sites describing earth building generally indicate a holistic approach to earth building, frequently focusing on buildings that are in harmony with the geology and flora of the building site, the use of natural materials in the construction process, and the natural energy efficiency of earth buildings. Information on the science and engineering of the various earth building technologies is very limited.

A demonstration of RE building construction was proposed for North Dakota. At the request of the North Dakota Industrial Commission (NDIC) Lignite Research Council, the Energy & Environmental Research Center (EERC) performed an investigation to evaluate the potential of North Dakota bottom ash and fly ash for use in RE construction. The work was funded jointly by NDIC and the U.S. Department of Energy through the Coal Ash Resources Research Consortium.

BACKGROUND

Rammed-Earth Construction

RE construction is an historical method of construction using earth compressed into a form similar to adobe. RE construction uses a native soil and equipment that compacts the earth into the wall or other structure configuration. Like other earth building techniques, RE requires earth or soil with a certain range of properties, and as RE buildings age, the RE cures and the strength and durability of the RE structure will increase. RE construction is less common than adobe, and special methods for construction of openings and other construction details are used.

The major differences between RE wall building and adobe bricks are probably attributable to climatic factors. Adobe bricks require rain-free periods of time in which to make and cure the bricks, thus placing some limitation on the geographic and climatic areas where they can be

used. RE walls, on the other hand, can be constructed in more humid climates where brick manufacture would be difficult or impossible. Although RE is typically associated with buildings in the Southwest, prior projects were conducted throughout the eastern United States and the Midwest, particularly during the middle of the last century (McHenry, 1984). In North Dakota, some soils are appropriate for RE construction without the use of additives as stabilizers; however, more frequently, North Dakota soils need some amendment to meet performance requirements for durability and strength. Additives are frequently used to add strength to RE and adobe (McHenry, 1984; Easton, 1996), although the need for improving the strength is questioned by some earth building proponents (Bourgeois and Pelos, 1989). The work reported in this document was designed specifically to evaluate North Dakota materials for use in RE, but the procedures used are applicable to materials from any location.

One of the main concerns for building officials regarding RE is quality control of the finished rammed wall. It is one thing to maintain a uniform quality in the mix proportions by making up test cylinders from the daily mixtures. It is an altogether different matter to maintain the same level of quality control in the finished wall, since this method of construction relies to the extreme on the quality of workmanship. One way to obtain the needed quality control information is to require that cores be taken from the finished wall and tested for compressive strength. However, this is not only expensive, but also destructive to the wall. Other less expensive and less destructive methods of obtaining this information are preferred. One potentially viable test for soil compaction can be performed with a nuclear density gauge (American Society for Testing and Materials [ASTM] D 2922-81, Method B) or other means. If compaction within the wall can be correlated with compressive strength, it would negate the need for coring. At the present time, such compaction testing procedures are not specifically written for RE walls.

The state of New Mexico has developed its own building specifications, found in the *New Mexico Adobe and Rammed-Earth Building Code* (see Appendix A). This is one of the few official codes for building RE structures. It lists a few specifications that deal with materials, construction procedures, and quality control. In RE construction, the uncompacted, damp soil is required to be compacted in lifts not to exceed 6 inches until suitable compressive strength is achieved. Average strength specifications exist for compressive (300 psi) and modulus of rupture (50 psi), but it is not clear if they apply to both RE and adobe blocks.

Adobe walls have low R-value (resistance to heat flow), because they commonly consist of 10- or 14-inch blocks covered with a thin stucco on the outside and thin gypsum plaster on the inside. Similarly, RE construction usually is thick-walled, and the proposed North Dakota RE project will have thick walls. R-values do not tell the full story in determining what is a high-quality, thermally efficient wall. The high heat storage capacity of a compressed soil wall means that it can keep a building's daytime temperatures cool in the summer and warm in the winter.

McHenry (1984) discusses the use of aggregate in adobe brick and indicates that sand, coarser aggregate, or vegetal material (straw, hay, or manure) may be added to balance the clay content of certain soils not well-suited to adobe. McHenry indicates that up to 30% coarse or fine sand may be required and that up to 15% gravel may be added. The percentage of aggregate added is soil-specific, and each soil must be evaluated to determine if aggregate is needed.

Further, test bricks must be produced and tested to evaluate the efficacy of aggregate addition. The potential of aggregates to change the R-value of adobe was not discussed, but the use of bottom ash, an aggregate-like coal combustion byproduct (CCB), was proposed for the North Dakota RE project, with the hypothesis that the bottom ash addition would improve the R-value of RE walls. Lignite bottom ash is environmentally benign and has properties similar to those of aggregate. The EERC investigation was designed to evaluate the use of bottom ash in RE with specific evaluation of the impact on the R-value.

Modern RE construction frequently uses stabilizers to enhance engineering performance and durability. Coal combustion fly ash and bottom ash have excellent potential for use in RE construction. They can be used as a low-cost alternative to portland cement and other stabilizers because of their cementitious properties as amendments or modifiers to many North Dakota soils. Past EERC studies indicate that lignite fly ash is environmentally benign and offers advantageous cementitious performance.

Typical Rammed-Earth Construction Procedures (Burlington Construction, 2000)

A successful earth construction project requires appropriate foundations, which includes the installation of electrical, mechanical, and plumbing elements before the slab floor (typically) is poured. Engineered concrete footings are required to support the RE walls. In at least some cases, reinforcing steel is placed vertically into the footings.

Static forms, either wood or concrete, are then set. A forming technique utilizing a movable or “slip” form was proposed for RE construction in North Dakota. This type of forming technique minimizes the cost of forming. Depending on the type of forming used, reinforcement and hardware are either added prior to or during the placement of the RE.

When the type of form selected is ready for the earth, the RE process is initiated by placing premixed earth inside the form and ramming it with appropriate ramming equipment, generally pneumatic air-driven rammers. Care must be taken during the ramming process not to damage the embedded plumbing and electrical pipes and boxes. Walls are usually kept damp for a week to cure. Walls constructed by either method are usually 18 to 24 inches thick.

Once the walls are completed and the floor slabs poured, the wood framing phase of the project begins. Pressure-treated wood plates are recommended where earth walls come into contact with wood walls. Wood stud walls should be attached to the earth walls with construction adhesive and concrete screws to minimize movement at the junction of dissimilar materials. The roof system is important because of the need to keep water from infiltrating the RE walls. It is recommended that all pneumatically impacted interior walls be plastered. All remaining finish work proceeds generally as it would with a conventionally built structure.

Coal Combustion Byproduct Characteristics

All coal contains minerals. These minerals are composed of inorganic constituents and become the ash or CCB that is collected following combustion. CCBs are available throughout the United States, but exhibit variability primarily related to the coal used and the combustion

system. The range of characteristics exhibited by CCBs makes them useful in numerous engineering and construction applications. However, it is important to evaluate the properties and performance of CCBs in considering their use for any specific application.

CCBs (fly ash, bottom ash, boiler slag, flue gas desulfurization [FGD] material, and fluidized-bed combustion [FBC] byproducts) display both physical and chemical differences related to coal type, combustion system, emission control system, and collection method. Fly ash is a finely powdered material comprised mainly of amorphous (glassy) spherical particles. Bottom ash is a coarse material with sintered and agglomerated amorphous particles. Boiler slag generally has the form of glassy pellets. FGD material is typically a crystalline fine powder, but may be a sludge (wet FGD) or a dry powder. Table 1 summarizes the physical and chemical variability of bottom ash and fly ash. Variability in composition and physical properties can be an indicator of variability in performance, but performance testing is the most reliable means to determine the performance of a specific material.

TABLE 1

Physical and Chemical Variability of CCBs

CCB Type	Particle Size	Particle Morphology	Color	Major Composition	Trace Element Composition
Fly Ash	High percentage < 325 sieve	Spherical	Tan to gray	Depends on coal source	Enriched in trace elements
Bottom Ash	Range from granular to ½ in.	Angular	Tan to black	Depends on coal source	Low concentrations

The bulk composition of fly ash is similar to that of many geologic materials. Fly ash is primarily composed of silicon, aluminum, iron, calcium, magnesium, sodium, potassium, and sulfur in association with oxygen as oxides, silicates, and aluminates. The combined silicon, aluminum, and iron content (reported as oxides) is frequently used to provide an indication of the pozzolanic or cementitious nature of fly ash (as in ASTM C 618). A combined value of 70% of these components indicates a pozzolanic fly ash, and a value of between 50% and 70% indicates a cementitious fly ash. A pozzolan is a material that sets up when combined with water and a source of calcium. A cementitious material sets up when combined with water alone. Thus another indicator of pozzolanic/cementitious behavior is the calcium content of fly ash. Higher calcium content (>15% as CaO) generally indicates a cementitious fly ash. Cementitious fly ashes are best suited for soil stabilization applications for road building and have the highest potential to be useful in RE.

Total trace element concentrations and trace element leachate concentrations are frequently determined for fly ash. Leaching is the best available test to evaluate environmental performance of fly ash. Variability is noted in both total and leachate trace element concentrations. The ranges of leachate concentrations for Resource Conservation and Recovery Act (RCRA) elements (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) fall below the RCRA limits for hazardous waste and usually below the primary drinking water standard limits.

Soil Characteristics

The behavior of a soil changes with a change in water content and is also a function of clay type and content. At a high water content, soil is in suspension, with the flow properties of a liquid. As the water content decreases, the soil becomes consecutively pastelike, sticky, then plastic, and finally, at a low water content, the soil has the properties of a solid. The physical state of a soil at a given water content is termed its consistency, which is a measure of the resistance of a soil to flow.

In considering soil characteristics, various terms are used to classify or specify the soils in order to evaluate if stabilization may be needed. The specific consistencies used for soil classification purposes are the liquid and plastic limits. The liquid limit (LL) is the water content, in percent by weight, at which a soil ceases to behave as a liquid and begins to exhibit plastic behavior. The plastic limit (PL) is the water content below which the soil is not plastic and crumbles when rolled. The plasticity index (PI) of a soil is defined as the LL minus the PL. The PI largely depends on the amount of clay present, and the strength of a soil increases as the PI increases. However, the tendency of a clay to expand when wet and shrink when dried also increases as the PI increases.

David Easton, in his book *The Rammed Earth House* (Easton, 1996), defines stabilization:

Stabilization is defined as the elimination of change, the creation of a steady physical state. Within the context of rammed-earth construction, stabilization is the elimination of the change in volume that occurs in a soil as it absorbs and discharges water. Stabilization does not always mean the addition of cement, because in some soils and under ideal conditions, it is possible to compact the soil tightly enough to create a wall which will resist moisture absorption and hence the tendency to expand in volume.

The soils used in RE are identical to those used in adobe bricks. A soil with small gravel aggregate, sand, silt, and clay will be most suitable. The durability and waterproof qualities of the wall are dependent on the clay content, which ideally will approximate 15%–18% of the soil. A higher clay content is allowable and desirable in soils used for RE construction. The moisture content is much lower initially in RE, and, therefore, the structure is less subject to shrinkage on drying.

Mechanical Properties

Most of the mechanical properties of adobe are not well characterized. Most of the work has been concerned with measuring the ultimate compressive strength to determine the effects of different soils, mix proportions, and specimen sizes on compressive strength. Little information has been reported on the creep strength and the moisture content of adobe. Most commonly for adobe bricks, a minimum compressive strength of 200 to 300 psi is recommended (*New Mexico Adobe and Rammed-Earth Building Code, see Appendix A*). The requirements for RE are generally the same as for adobe, so the same level of minimum compressive strength can be used.

Soil, because it comes from a naturally occurring ground source, frequently has adequate moisture for use directly in RE walls. It must be damp, but not wet. The precise proportions of aggregate, clay, and sand are not critical, and a simple field test will determine the readiness of a soil for use. First, it should appear damp, but not wet. A handful of the soil can be squeezed into a firm ball readily by hand. In this test, a soil with a moisture content that is too high will feel sticky and will not form a firm, solid ball when squeezed. On the other hand, if too little moisture is present, the soil will not compact and hold together at all. The successful compacted soil ball will be firm and solid, but neither hard nor sticky. The hand-compacted soil ball can be dropped onto a firm surface from a distance of approximately 3 feet. If the soil ball shatters, the moisture content is adequate. If it does not, too much moisture is present.

PROJECT PLAN

Several issues need to be evaluated prior to the demonstration of the RE building technology in North Dakota: 1) appropriateness of the local soils, 2) the use of coal combustion bottom ash and fly ash and other additives such as portland cement, and, 3) the performance of RE in the North Dakota climate. The materials evaluated for this project represent one source of soil, fly ash, and bottom ash. Soils and CCBs from other sources may need to be evaluated at the laboratory scale on a case-by-case basis. A review of the RE technology for practicality and an evaluation of market potential for RE buildings in North Dakota and the region were also part of the EERC effort.

The overall goal of this work was to evaluate the end product of the RE process for performance and durability. Specific objectives were:

- To determine a mix design based on local materials.
- To perform tests to ensure environmental acceptability.
- To perform tests to verify the long-term durability of the RE block.
- To perform a preliminary evaluation of the RE technology proposed and the market potential for RE construction in North Dakota.
- To investigate CCBs as a low-cost alternative to current stabilizers commonly used.
- To compare R-values of RE with and without bottom ash to determine if the addition of bottom ash increases R-value.

EXPERIMENTAL

Although RE has been used for centuries, there are no well-established engineering standards available for soil–fly ash or soil–bottom ash mixes. The fly ash industry has established many tests to evaluate fly ash. There are also numerous standardized tests to evaluate soil characteristics. Although these tests provide a starting point for RE evaluation, many of the tests that are used for soil or fly ash as individual components are not applicable to RE because the nature of the composite is different from that of either component. Standardized tests to evaluate soil–fly ash mixes do exist, but the tests are performed to establish appropriateness for roadbeds and fill, not RE. Consequently, establishing engineering standards for RE is warranted.

Mix Design and Performance Testing

Sample Collection and Soil Testing

A 55-gallon barrel of soil was obtained from the location of the proposed field demonstration, described as New Sanish soil (low clay content). Laboratory tests performed to characterize the soil were Atterberg limits (ASTM Method D 4318) and soil classifications (Unified Method and the American Association of State Highway and Transportation Officials [AASHTO] Method M 145-91). These are accelerated methods of determining durability. The specific test methods used are named in the Durability section. A visual physical examination of the soil was also performed.

The LL and PL are widely used, primarily for soil identification and classification according to the AASHTO and Unified Method. The specific consistencies that are used for soil classification purposes are the LL and PL. The LL is the water content, in percent by weight, at which a soil ceases to behave as a liquid and begins to exhibit the behavior of a plastic. The PL is the water content below which the soil is not plastic and crumbles when rolled. The PI of a soil is defined as the LL minus the PL. The PI largely depends on the amount of clay present, and the strength of a soil increases as the PI increases. However, the tendency for a clay to expand when wet and shrink when dried also increases as the PI increases.

The AASHTO-recommended practice for classifying soils is test designation M 145-91. The group classification should be useful in determining the relative quality of the soil material for use in earthwork structures, particularly embankments, subgrades, subbases, and bases. The Unified Soil Classification system is rather widely used inside the United States by organizations such as the Army Corps of Engineers and the Bureau of Reclamation.

Fly ash and bottom ash samples were obtained from Great River Energy's Coal Creek Station Power Plant at Underwood, North Dakota. The Coal Creek Station uses Falkirk mine lignite as its fuel. Type I–II portland cement was obtained from a commercial source in Grand Forks, North Dakota.

Mix Designs

Mix designs were developed using a two-phase approach. First, a matrix of trial mixtures including various combinations of soil, bottom ash, fly ash, and cement was prepared and evaluated for strength development. Strength was used as the primary measure of performance in the first round of mix design, but the various mixes were also observed for physical handling properties and ease of handling as the test specimens were made.

Twenty-two mix designs were used to determine maximum dry density at optimum moisture content and subsequent compressive strengths. All the mix designs are identified in the Results section. A total of 28 mix designs were originally intended for this research effort. To ensure adequate materials would be available to evaluate the various combinations of soil and additives, it was necessary to omit six mixes from the test matrix. It was decided to omit mixes that used cement only as the additive because the remaining mixes utilizing cement only represented an expected range of performance for the cement additive use alone. Previous EERC research has shown that small amounts of cement will greatly enhance the strength development of a stabilized soil mixture and that cement generally produces greater strengths than cementitious fly ash from any source (Pflughoeft-Hassett and others, 1996). Using cement–fly ash mixtures as a soil additive also generally increases strength over soil–fly ash mixtures.

A total of 22 mixes were made (see Table 1), and test cylinders were produced and cured for 7 days at 100% humidity at room temperature (ambient temperature of about 72°F). Optimum moisture and maximum dry density were also determined for each specimen produced. The strength of each specimen was also determined after the 7-day curing time. Strength was the preliminary criterion used to evaluate the potential engineering performance of the RE specimens and identify mixes for further evaluation. Strengths of 200 to 300 psi are recommended in the New Mexico Adobe and Rammed-Earth Building Code (See Appendix A), and a summary of building codes for earth construction (McHenry, 1984) also indicates the desirable level of strength from 90 psi (uncured RE) to 300 psi (cured RE). Based on this information, it was decided to use these levels of strength as a guideline in selecting a limited number of mixes for additional testing. Strength development was the lowest in soil only and soil–bottom ash mixes. The addition of fly ash and cement increased the strength development.

Based on these preliminary strength development tests, six mixes and a control soil sample were identified for further durability testing.

Durability

Final products representing the six selected mixes and a control sample of soil only were tested for durability. Durability testing included freeze–thaw tests that follow ASTM procedures for soil stabilization. Wet–dry cycles and a vacuum saturation procedure were also used to help determine durability.

The standard compaction method for compressive strength testing, ASTM D698-91, Laboratory Compaction Characteristics of Soil Using Standard Effort Procedure A, was used to prepare samples for durability testing. In this method, the mixtures are compacted in a 4-in.-

diameter mold with a 5.5-lbf rammer dropped from a height of 12 in., producing a compaction effort of 12,400 ft-lbf/ft³. Three compaction layers are placed at 25 blows per layer.

The soil cylinders were each sealed in a plastic, airtight, moisture-proof bag and cured for 7 days. Samples were then tested for compressive strength development again, and durability tests were initiated. The durability testing includes freeze–thaw and wet–dry tests that follow ASTM procedures for soil stabilization. The specific procedures are ASTM D 559, Wetting and Drying Compacted Soil–Cement Mixtures, ASTM D560, Freezing and Thawing Compacted Soil–Cement Mixtures, and ASTM C 593, Fly Ash and Other Pozzolans for Use with Lime, a vacuum saturation strength-testing procedure. The freeze–thaw and wet–dry procedures are methods to evaluate soil mixtures for weight loss after environmental exposure. The mixtures tested for durability were the following:

- Mix 1: 100% soil
- Mix 4: 70% soil and 30% bottom ash
- Mix 8: 80% soil and 20% fly ash
- Mix 11: 80% Base 1 (70% soil and 30% bottom ash) and 20% fly ash
- Mix 13: 80% Base 1, 10% fly ash, and 10% cement
- Mix 14: 90% Base 1 and 10% fly ash
- Mix 16: 90% Base 1, 5% fly ash, and 5% cement

The many different clay minerals and clay mixtures found in soils each have unique properties that can impact the final product. Using additives increases the possibilities for cementing or binding reactions and/or products in the various mixes. Several specimens from the final mixes were evaluated by scanning electron microscopy (SEM) to determine the degree of stabilization of the clay minerals.

Scanning Electron Microscopy

Four samples were examined using SEM to visualize the degree of cementation, or binding ability, of some of the mixes. These samples were selected on the basis of their mix and strength development. The samples were prepared by breaking off a small piece of the sample submitted in order to look at a freshly exposed surface that broke along a natural plane of weakness. The samples were then mounted on a carbon holder using both conductive tape and colloidal conductive paint. The samples were finally gold-coated before being examined. The four samples chosen were Mixes 4, 11, 14, and 16. Table 2 shows the composition for each of those samples.

R-Value Testing

Incorporating bottom ash in RE is a potential means of improving its insulation properties. Because there is no standard for establishing R-value in RE buildings, EERC researchers used ASTM and Internet resources to select a method to determine R-value for RE samples. Several commercial laboratories were contacted to determine the best test method for the RE samples available. It was decided that the most practical approach was to use ASTM Method C 518 at a commercial laboratory.

TABLE 2

Composition of Samples Examined by SEM	
Sample	Mix
Mix 4	Base 1 (70% soil and 30% bottom ash)
Mix 11	80% base and 20% fly ash
Mix 14	90% base and 10% fly ash
Mix 16	90% base, 5% fly ash, and 5% cement

EERC researchers prepared two samples to meet the requirements for this test procedure. The two samples contained soil and cement in the same proportions (65% and 10%, respectively). Bottom ash (15%) was added to one specimen, and fly ash (15%) was added to the other specimen. Comparison of the results of R-value testing on these two samples was used to evaluate the effect of bottom ash on the insulation properties of RE.

Environmental Properties

The environmental properties were addressed to ensure that the RE blocks do not pose a health threat from use, runoff, and ultimate disposal. The blocks produced were tested for leachability as well as their potential for radon emanation. All of the materials—soils, clays, and ashes—were tested for their major, minor, and trace element chemistry. If the concentrations of trace elements are very low, then leachate from runoff or ultimate disposal is of little concern.

Samples of stabilized soil were obtained from the engineering performance tasks. Three of these samples were selected as the focus for the environmental work in addition to the raw materials used: soil, bottom ash, fly ash, and cement. Samples were prepared and submitted to appropriate laboratories for total composition determinations. Prepared samples were also submitted for leaching and subsequent leachate analysis.

Leachate analysis was conducted in an 18-hour test using distilled, deionized water at a 20:1 ratio with end-over-end agitation of the containers. Testing was done to establish the level of trace elements designated as hazardous under RCRA, with a couple of exceptions. Silver is listed under RCRA, but testing was not conducted for this element. Industrywide testing has determined that this element is practically nonexistent in fly ash. However, boron was added to the group tested because of plant toxicity and concerns for possible damage to landscaping surrounding a RE structure.

In order to perform a comparative test of the raw materials for radon emanation, an Internet-based literature search was performed. Results of this search indicated that a standard laboratory test for radon emanation from RE has not been developed, so EERC researchers developed a simple test to evaluate the comparative radon emanation of the raw materials. The test uses a large bottle in which a layer of the raw material is placed. The raw material was placed in a level bed of the same depth for each material. The samples were leveled and lightly compacted manually to minimize voids within the sample beds. An active carbon-based radon

collection device obtained from a commercial radon-testing laboratory was situated above the bed material, and the bottles were sealed. Emitted radon was accumulated for 7 days. The radon collection devices were then sent to the commercial laboratory to determine the radon collected.

Feasibility

A brief feasibility study was performed in two steps. The first was an evaluation of the product and building design by a qualified builder who could evaluate RE as a technology competitive with traditional building technologies. The second step was to survey the building community in North Dakota for a history of alternative building technologies such as concrete buildings, block, or any other nontraditionally built homes and buildings.

Information was gathered through Internet resources, books and publications, and interviews with individuals involved in home building in general and RE construction in particular. Key issues include soils available for construction, control of surface and rain water on the wall exterior, wall thickness, labor costs, quality control in wall construction, surfacing of RE inside and outside walls, and the effects of climate on the building's durability.

While there are many RE buildings located in other parts of the United States, obtaining information related to the Midwest was more difficult to find. Individuals and groups within the North Dakota building industry were polled to determine the viability of RE home/commercial construction in North Dakota and the region.

Another aspect of the feasibility study was to evaluate the use potential for North Dakota fly ash and bottom ash in RE construction. EERC researchers estimated fly ash and bottom ash additions required to produce an earth mix appropriate for RE using an example mix from the durability testing. These estimates were applied to an intermediate-size home, and a calculation was made to determine the amount of fly ash and bottom ash that would be used in a typical home. This information was used to determine an estimate of North Dakota ash use in RE annually in North Dakota. The export of North Dakota ash to regional locations for RE construction has been proposed, so a summary of the availability of ash regionally was assembled, transportation costs for fly ash and bottom ash were estimated, and the potential for RE construction was estimated based on North Dakota information.

RESULTS AND DISCUSSION

Mix Design and Performance Testing

Soil Testing

There are few stabilized soil specification standards available for RE; however, the materials themselves are those commonly used for roadbed construction. Although the tests used to evaluate soils for mix design and performance testing were specifically designed for evaluation of roadbed durability, they are the most appropriate methods for classifying soils for RE construction. Atterberg is used for determining LL and PL and gives an alphanumeric

classification useful to civil engineers. AASHTO and the Unified Method give a description of soil classification more useful to the layperson and are more likely to describe soils in engineered applications.

Laboratory determination of Atterberg limits indicated the soil to be 57% less than the 200-mesh sieve, with a LL of 35.5% and a PL of 26.0%. According to the Unified Method of classification, the soil is in category CL, and according to the AASHTO method, it has a classification of A-6. The physical description is sandy, lean clay with gravel.

Compressive Strength Testing

The soil was initially air-dried, crushed, and sieved through a No. 4 mesh sieve prior to being used in the compaction method. The results of the compaction procedure are also given in Table 3 for maximum dry density and optimum moisture content. Each sample cylinder was retained, cured 7 days, and tested for compressive strength. Graphs of each mix design, represented as moisture content versus dry density and compressive strength, are contained in Appendix B. The curves were computer-derived using a second- or third-order best fit. The maximum dry density and optimum moisture content were derived from these graphs. The strength relation is also included. Appendix B contains charts of various soil mixes and their resulting performance. As stated earlier, the 7-day strength was used to identify mixes with potential to be used in RE construction. Six mixes and one control containing soil only were selected for durability testing.

Durability Testing

The results of performance testing are presented in Table 4 for strength and weight loss after the freeze–thaw and wet–dry procedures. All samples for durability testing were prepared at optimum moisture conditions as determined previously. All samples were cured for 7 days prior to testing. The following mixtures were evaluated:

- Mix 1: 100% soil
- Mix 4: 70% soil and 30% bottom ash
- Mix 8: 80% soil and 20% fly ash
- Mix 11: 80% Base 1 (70% soil and 30% bottom ash) and 20% fly ash
- Mix 13: 80% Base 1, 10% fly ash, and 10% cement
- Mix 14: 90% Base 1 and 10% fly ash
- Mix 16: 90% Base 1, 5% fly ash, and 5% cement

The soil–bottom ash mixture was included because it had been hypothesized that bottom ash could be used to improve the insulative properties of the soil. It was important to evaluate the engineering performance of that mix in addition to evaluating the impact of bottom ash on the R-value. Additional specimens were prepared and tested using standard durability tests. Two of the selected mixes exceeded 300 psi. Three of the selected mixes exceeded the recommendation for strength for uncured RE (90 psi). Those mixes that exceeded 300 psi included cement in the mix. Mixes that incorporated either fly ash or fly and cement performed better than the soil control sample and the soil–bottom ash mix. Additional durability tests also indicated improved

TABLE 3

Soil Mixtures for Determining Maximum Dry Density at Optimum Moisture Content					
Mix ID No.	Soil, Fly Ash, Bottom Ash, and Cement, wt%	Optimum Moisture Content, %	Max. Dry Density, pcf	7-day Strength at Optimum Moisture Content, psi	Maximum 7-day Strength, psi (moisture content, %)
1	100 S	16.7	107.7	50	56 (12.2)
2	90 S, 10 BA	15.8	108.1	53	58 (13.5)
3	80 S, 20 BA	16.5	107.6	45	58 (13.5)
4	70 S, 30 BA	14.0	108.1	50	62 (12.1)
5	90 S, 10 FA	15.3	109.5	80	98 (14.2)
6	90 S, 10 C	17.8	102.6	480	490 (16.5)
7	90 S, 5 FA, 5 C	16.8	104.7	380	390 (17.1)
8	80 S, 20 FA	14.7	112.0	85	111 (12.3)
9	80 S, 20 C	17.1	107.7	1000	1023 (14.2)
10	80 S, 10 FA, 10 C	15.7	107.2	640	740 (14.7)
11	80 Base 1 (70 S, 30 BA) 20 FA	12.1	114.7	112	117 (11.9)
13	80 Base 1, 10 FA, 10 C	13.8	110.8	425	595 (10.2)
14	90 Base 1, 10 FA	12.8	111.9	82	96 (10.7)
16	90 Base 1, 5 FA, 5 C	13.8	108.8	390	396 (13.0)
17	80 Base 2 (80 S, 20 BA) 20 FA	12.2	114.8	102	115 (9.7)
19	80 Base 2, 10 FA, 10 C	15.1	109.8	734	736 (14.7)
20	90 Base 2, 10 FA	13.8	111.2	84	86 (14.0)
22	90 Base 2, 5 FA, 5 C	15.0	109.6	420	430 (14.5)
23	80 Base 3 (90 S, 10 BA) 20 FA	13.3	111.4	92	100 (9.6)
25	80 Base 3, 10 FA, 10 C	16.8	108.6	650	705 (14.7)
26	90 Base 3, 10 FA	14.9	110.2	72	96 (13.4)
28	90 Base 3, 5 FA, 5 C	16.2	107.0	376	376 (16.5)

Note: S = soil, BA = bottom ash, FA = fly ash, C = cement, psi = pounds per square inch, pcf = pounds per cubic foot.

TABLE 4

Mix Design	Strength Testing and Performance Testing					
	7-Day Strength, psi	Vac. Sat.¹ Strength, psi	Wet-Dry Strength, psi	Freeze-Thaw Strength, psi	Wet-Dry Weight Loss, %	Freeze-Thaw Weight Loss, %
1	52	6	0	418	–	5.1
4	50	16	0	418	–	7.7
8	107	64	207	796	16.0	2.9
11	123	60	916	637	3.2	2.4
13	788	689	3344	2627	1.8	1.2
14	100	52	557	816	13.1	3.6
16	462	398	2030	1712	2.4	2.0

¹ Vacuum saturation procedure.

performance by the mixes with fly ash and fly ash–cement additions over the soil and soil-bottom ash. The mixes with cement performed the best on all strength and durability tests performed.

On the basis of the durability testing results, three mix designs, Nos. 11, 14, and 16, could be recommended for RE construction. The results indicated that the soil and soil–bottom ash mix would not be recommended. A cementitious additive is needed to produce a stronger and more durable RE. It is evident from the results in Table 4 that cement enhances the durability of the earth tested. Based on these results, the use of cement or a combination of cement and fly ash is recommended to produce a durable RE product meeting the 200- to 300-psi minimum requirement.

In related research on soil stabilization using fly ash, compressive strengths have significantly increased after curing for longer periods of time than 7 days. Strengths at 14 and 28 days have often doubled compared to those occurring at 7 days. The use of cement is an additional variable, representing an added step in field preparation and increased cost, but small amounts have been shown to add a significant improvement in durability. Slight variations in these mix designs using a larger ratio of fly ash than cement could also be an option. Extrapolating the performance test results based on previous research, it is reasonable to conclude that fly ash-amended soils will attain adequate strength to be used for RE; however, the longer curing times needed for soil–fly ash mixes are not addressed in the building code (Appendix A). For this reason, it is recommended that fly ash be supplemented with cement or cement alone be used as the cementitious additive to produce RE with adequate durability. As noted, cement generally provides good strength development in soil applications, and the addition of fly ash to a cement–soil mix would not provide any performance improvement. The availability and cost of each material would dictate the final levels of usage.

Durability results also indicate that the soil–bottom ash mix performs the same as the soil only. Bottom ash does not provide any advantage or disadvantage for engineering performance of the soil.

Scanning Electron Microscopy

The four samples examined with SEM showed various degrees of cementation. Figure 1 is a photomicrograph of Mix 4, the 70% soil and 30% bottom ash mix referred to as the base mix. The particles are clearly not bound together, and any strength associated with this mix is likely attributed to the angularity of the particles causing high friction in close proximity to each other. This sample was difficult to prepare for SEM examination because it was so friable.

Figure 2 shows a fly ash grain from Mix 14 (90% base and 10% fly ash) that is cemented to some degree to the soil particles surrounding it. Upon close examination, a few smaller fly ash spheres can be seen thoroughly incorporated into the matrix. The area of the sample where this image was taken shows fairly good cementation to the point that few individual grains can be made out.

Figure 3 was taken from Mix 11, which was 80% base and 20% fly ash. Several fly ash spheres can be seen imbedded in the soil matrix. Cements have formed and obscure most of the grain boundaries.

Figure 4 is from Mix 16, which contained 90% base, 5% fly ash, and 5% cement. Individual grains can still be distinguished, and the cementitious growths between those grains can be recognized.



Figure 1. SEM of Mix 4, 70% soil and 30% bottom ash.

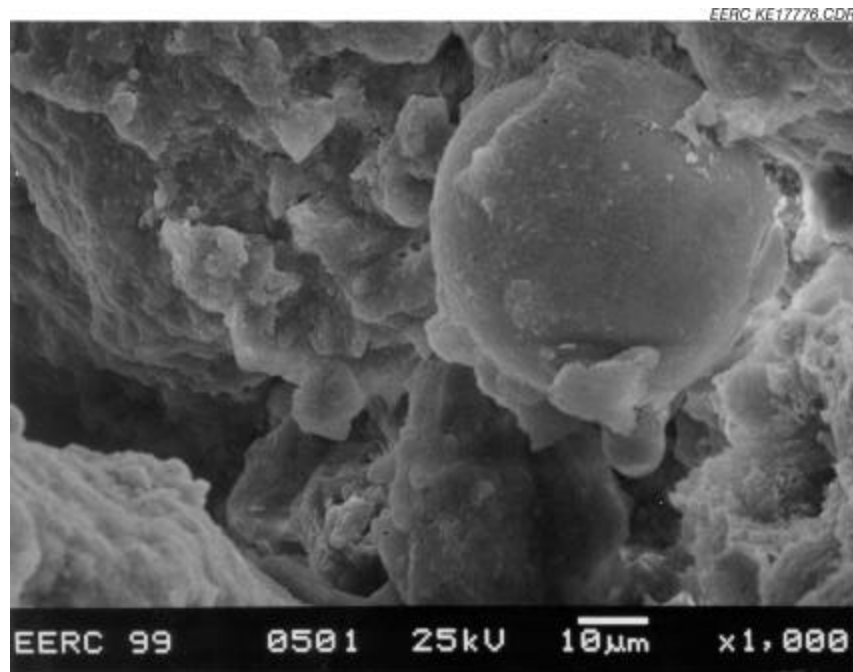


Figure 2. SEM of Mix 14, 90% base and 10% fly ash.

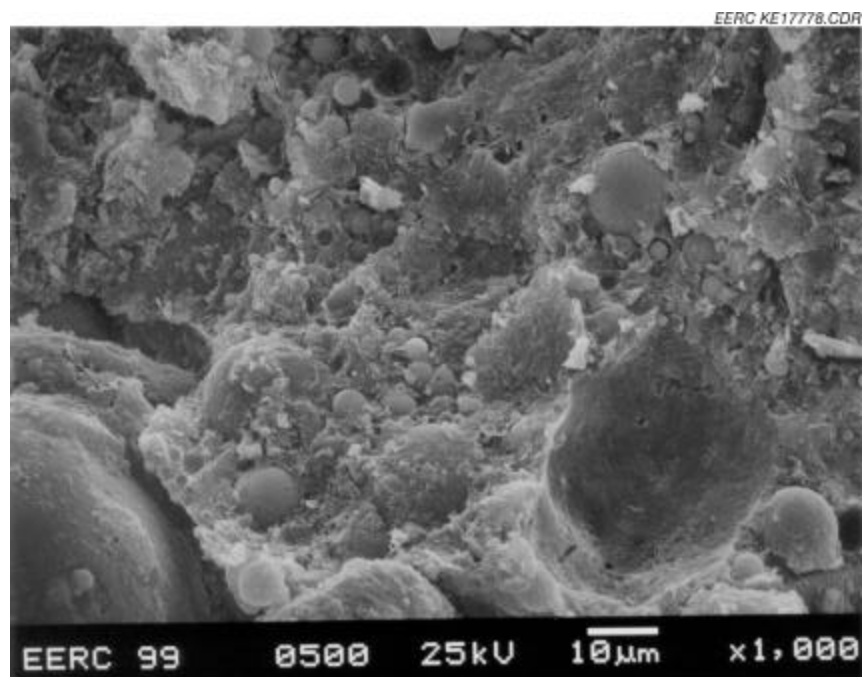


Figure 3. SEM of Mix 11, 80% base and 20% fly ash.

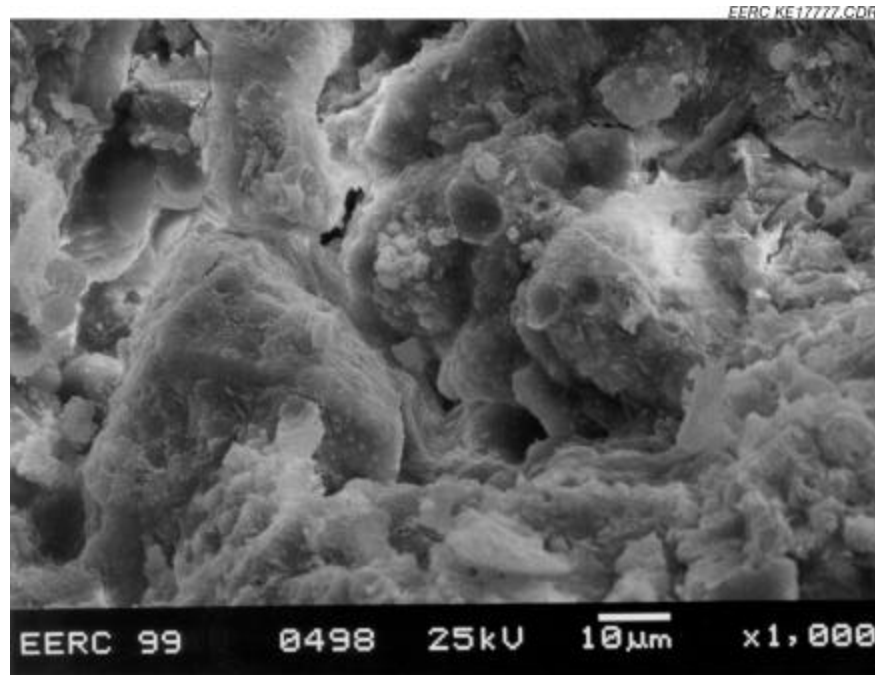


Figure 4. SEM of Mix 16, 90% base, 5% fly ash, and 5% cement.

R-Value Testing

The R-value ($\text{m}^2\text{K/W}$, which is the standard R-value expression) was determined on 1-in. cubes at 30° and 100°C. The average measured R-value for 1-in. cubes is reported in Table 5. For the North Dakota demonstration of RE, 30- to 36-in. walls have been proposed, so a calculated R-value for a 36-in. wall is also included in Table 5. The addition of 15% bottom ash provided a 14% increase in R-value over the sample without bottom ash, consistent with the hypothesis of the individual proposing RE construction in North Dakota.

TABLE 5

Comparative R-Value Testing		
Sample	Measured R-Value (1-in. specimen)	Calculated R-Value for 36-in. Wall
Soil and Cementitious Material	0.079	2.84
Soil, Cementitious Material, and 15% Bottom Ash	0.091	3.24

The R-values for the RE samples are lower than published R-values for RE walls (0.25/in., or 4.5 for an 18-in. wall (New Mexico Energy, Minerals, and Natural Resources Department, Energy Conservation and Management Division, 2000) and significantly lower than R-values for traditional insulation such as glass wool (R-value of 15 for a 3.5-in.-thick batt) or styrofoam (R-value of 5 for 1-in.-thick board). As noted in numerous sources, R-value alone does not provide a good indication of the performance of earthen buildings relative to temperature control or energy use. Heat capacity is also an important factor, and it is generally agreed that earthen walls exhibit high heat capacity. An evaluation of the heat capacity of various mixes with and without bottom ash would provide additional information to understand the performance of these materials.

The R-value results indicate that addition of bottom ash will improve the insulation properties of the RE walls. In considering bottom ash as an additive to RE, it is important to test the bottom ash with the specific soil to be used, as some soils may contain a sand component that would preclude addition of bottom ash, which is aggregatelike in its properties. The use of bottom ash to improve R-value must be balanced with the strength and durability of the final RE mix.

Environmental Performance of Coal Ash in Rammed Earth

Chemical Composition and Mobility

Samples of stabilized soil were obtained from the engineering performance tasks. Three of these samples were selected as the focus for the environmental work in addition to the raw materials used: soil, bottom ash, fly ash, and cement. Samples were prepared and submitted to appropriate laboratories for total composition determinations. Prepared samples were also submitted for leaching and subsequent leachate analysis. Table 6 shows the results of the chemical analysis.

Leachate Analysis

Leachate analysis results are shown in Table 7. It can be seen that maximum contaminant level (MCL) and maximum contaminant level goal (MCLG) levels are exceeded for chromium and selenium in fly ash leachates. Concentrations for these two elements in the fly ash leachates are well below the universal treatment standards (UTS) values, but more significantly, leachates from the soil mixes had concentrations below all limits, with the exception of boron. Boron concentrations in the fly ash, Mix 11A, and Mix 14A exceeded short-term irrigation standards noted in Table 7. Boron leaching might be an issue in the use of some fly ash in RE mix designs because of its high degree of mobility and its potential to hinder plant growth. As already noted, water management is critical in earth building, which is the primary reason for using stucco or other surfacing on RE and other earth-constructed buildings and designing the site and structure to eliminate the potential for water infiltration into the wall structures. For these reasons, researchers concluded that the potential for leachate generation is extremely low from a well-constructed RE building. The issue of leachability of trace elements would vary with the ash source and other binders, such as cement, but because of the low potential for leachate generation, the EERC concludes that the use of fly ash in RE is environmentally sound.

TABLE 6

Chemical Composition of Raw Materials

Major/Minor, wt%	Fly Ash	Bottom Ash	Cement	Soil
Silicon Dioxide, SiO ₂	46.66	47.39	21.48	65.51
Aluminum Oxide, Al ₂ O ₃	15.56	14.61	4.84	11.11
Iron Oxide, Fe ₂ O ₃	7.85	9.49	2.25	2.79
Total (SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃)	70.07	71.49	28.56	79.41
Calcium Oxide, CaO	17.03	17.31	62.79	7.61
Magnesium Oxide, MgO	5.01	5.46	2.89	2.12
Sodium Oxide, Na ₂ O	3.07	1.37	0.42	1.30
Potassium Oxide, K ₂ O	1.90	1.40	0.36	1.95
Titanium Dioxide, TiO ₂	0.56	0.53	0.19	0.39
Manganese Dioxide, MnO ₂	0.10	0.12	0.07	0.08
Phosphorus Pentoxide, P ₂ O ₅	0.28	0.22	0.39	0.19
Strontium Oxide, SrO	0.33	0.31	0.06	0.03
Barium Oxide, BaO	0.56	0.50	0.10	0.07
Sulfur Trioxide, SO ₃	1.03	0.49	3.52	0.13
Loss on Ignition	0.07	0.82	0.66	6.73
Moisture, as-received	0.02	0.32	0.39	1.61
Traces, µg/g				
Arsenic	132	40	9	10
Barium	5220	4300	706	724
Boron	1320	901	130	68
Cadmium	0.7	0.2	0.4	0.2
Chromium	59	45	45	37
Lead	31.8	8.7	31.8	11.7
Mercury	0.3	0.9	0.3	0.9
Selenium	9.9	<0.4	<0.4	<0.4

Radon Emanation

According to the U.S. Environmental Protection Agency (EPA) (1994) and the American Lung Association (1993), radon, a colorless, odorless gas, is a national indoor air pollution issue. Indoor radon exposure is estimated to be the second leading cause of lung cancer, responsible for thousands of deaths each year. The major source of high levels of radon in homes is the soil surrounding the home.

Radon (²²²Rn) is a radioactive gas with a half-life of 3.825 days that is produced by the radioactive decay of radium (²²⁶Ra). Radon can be a problem because it is a gas and can migrate out of earth or construction materials if ²²⁶Ra is present. Since radium, which originates from

TABLE 7

18-hour Deionized Water Leachate, µg/L											
	Bottom Ash	Fly Ash	Soil	Cement	Mix 11	Mix 14	Mix 16	MCL	MCLG	UTS	STI ¹
Arsenic	6.8	15	<4	<4	13	14	<4	50	NA ²	5000	NA
Barium	276	945	73	1460	343	279	373	2000	NA	21,000	NA
Boron	1840	10,600	<200	<200	2370	2350	600	NA	NA	NA	2000
Cadmium	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	5	NA	110	NA
Chromium	9.9	178	<1	82.1	34.3	18.8	49	100	NA	600	NA
Lead	<2	<2	<2	3.6	<2	<2	<2	NA	15	750	NA
Mercury	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	2	NA	25	NA
Selenium	<2	110	<2	<2	<2	<2	<2	NA	NA	5700	NA

¹ Short-term irrigation standard.

² No limit has been set by the government for these parameters.

uranium-238, can be present in numerous geologic materials, radon infiltration into buildings can be problematic under certain conditions.

Coal combustion ash generally has concentrations of radionuclides similar to other natural materials (Zielinski, 1998), but because of the health issues related to radon exposure, it was decided to evaluate all materials on a comparative basis to provide an indication of any radon-related issues.

Because RE construction uses soil as the primary building material for all wall components of a home, radon emanation from the soil and other potential RE components is of interest. The goal of the radon emanation evaluation for this effort was to identify any materials with high radon emanation potential. Comparative radon emanation experiments were performed using soil, fly ash, bottom ash, and cement. The same raw materials used in the preparation of other test specimens were used for this task. Radon was determined using a commercial laboratory after accumulation on activated carbon packets. The experiments were carried out as described below.

Samples of 300–400 g of each raw material were placed in a 3.5- to 3.8-cm-deep layer in the bottom of 2-L bottles. Since each bottle had a measured total volume of 2.27 L, the remaining headspace was approximately 2 L. The layer of raw material was compacted by gently tapping the bottle on a solid surface until no additional compaction was observed. An activated carbon packet was suspended in each bottle and allowed to accumulate radon for 8 days. After this 8-day accumulation time, the experiments were terminated and the carbon packets were sent to a commercial lab for radon determination. Results for the radon determination are shown in Table 8.

The results shown above are not total radon production as would be indicated by a determination of radium in each of the samples. This would normally be a much higher number. Rather, the radon emanation values represent the small fraction of radon that was able to escape from the sample due to diffusion. Because ^{222}Rn has a half-life of 3.825 days, most of the produced radon decays to solid daughter products before reaching the surface of a finely powdered material.

TABLE 8

Radon Emanation Results	
Material Tested	Amount Emanated, picocuries/L
Soil	1.2
Fly Ash	< 0.3
Bottom Ash	< 0.3
Cement	< 0.3

The average indoor level of radon is estimated to be about 1.3 pCi/L (picocuries/liter), and 0.4 pCi/L of radon is typically found in outside air. A picocurie is a measurement of radioactivity equal to 2.22 nuclear transformations per minute. EPA and the American Lung Association recommend action to reduce indoor levels of radon that exceed an annual level of 4 pCi/L or greater. The EERC test design measured only the radon emanation of materials in a lightly packed situation. It is anticipated that the radon emanation from RE would be lower because the RE construction technique would result in a very compacted final product with greatly reduced permeability. Additional tests with actual RE specimens would be required to estimate radon emanation in a RE building and, thus, calculate potential indoor radon concentrations.

The results shown above indicate that the only significant source of radon emanation is the soil. The results of this evaluation are material-specific, so any different material should also be evaluated prior to use in RE construction. For Coal Creek Station fly ash and bottom ash, the results indicate that these materials are environmentally safe from the standpoint of radon emanation. The cement evaluated was also environmentally safe.

Feasibility

Currently, only one RE home is reported to be in use in western North Dakota. Although numerous attempts were made to contact the RE homeowner, EERC researchers were unable to speak directly to the homeowner. From information provided by one interested party in the RE effort, it is understood that the home was built by the owner in 1997.

Other RE homes were built in North Dakota between 1900 and 1950, as were many RE homes throughout the United States. Because RE is typically encased in exterior and interior surface materials, it is difficult to determine if there are existing buildings, or portions of buildings, still in use, since the homeowner may not even be aware of the construction methods used. Many of the North Dakota RE homes are no longer in use, and as far as can be determined, are no longer even in existence. As one of our state architectural historians stated, several are “slipping back into the earth [they] were created from.” At least one of the historical RE homes in North Dakota was located on a reservation. No records were found detailing any history of the occupancy of any North Dakota RE homes, so the EERC was not able to determine specific reasons why these homes were demolished.

Nontraditional home building in North Dakota was discussed with Loren Abel of the East Grand Forks Northwest Technical College (NTC) (personal communication, October 29, 1999). Mr. Abel is an instructor of construction technology at NTC and also is a construction contractor. Mr. Abel’s NTC classes have worked on several local building projects, including the construction of an earth-sheltered home. Mr. Abel was not familiar with RE construction, but talked about several issues relating to the construction of nontraditional homes and the earth-sheltered home that was built by NTC. In Mr. Abel’s opinion, the most significant issue for nontraditional homes in any market is the training and experience of labor for the specific type of construction. NTC and other similar regional institutions work to provide a broad base of experience for students in construction technology, but since many nontraditional building styles are slow to be accepted, the labor force may not be experienced. It was also pointed out that

nontraditional homes may require nontraditional maintenance and upkeep of which the homeowner needs to be aware.

Regarding earthen homes, Mr. Abel brought up some relevant issues from his experience with earth-sheltered homes. In earthen homes in the North Dakota climate, moisture and cold spots were indicated by homeowners in winter months. The owners of the earth-sheltered home built by NTC indicated that the thick walls resulted in low-light situations, and the nonstandard, deep-set windows required nonstandard window treatments, adding to the cost of finishing the home. Mr. Abel indicated that earth-sheltered homes have not been in demand in the Grand Forks area or elsewhere in North Dakota in his experience.

In discussions with research staff at the National Association of Home Builders (NAHB) (personal communication, March 14, 2000) general information on RE construction was obtained:

- RE construction is typically found in the southwestern United States.
- Labor costs are the major cost associated with RE construction.
- RE homes are so few in number in the United States that the number is not included in a national survey of types of homes built. Even a larger category of earthen homes is not included.
- RE construction is best suited to dry climates where the temperatures are moderate and fluctuate on a shorter-term basis.
- Control of water to minimize contact with the RE is an important design factor.

Mr. Cameron Duncan, the NAHB contact, indicated a personal preference for RE construction and expressed a desire to live in a RE home. After offering his positive opinion about RE construction, he indicated that he personally would have reservations about building a RE home in North Dakota because of the climate. He indicated that any water issues could be adequately addressed by selecting an appropriate site for the home and using proper grading and overhangs. His greater concern was the long-term cold weather. While he did not offer any documentation, he indicated that with long cold periods, an earthen home or concrete home could become cold and damp. The optimal climate for a RE home is a moderate climate where it is possible to take advantage of warm days to warm the walls in cool seasons and cool nights to cool the walls in warm seasons. It is best to have these daily warm-cool cycles to take advantage of the insulative and heat storage capabilities of the earthen walls.

David Easton (Easton, 1996) and Rammed Earth Solar Homes Incorporated (RESHI) (personal communication, March 16, 2000) both have experience in constructing RE homes, and both indicated that an additive can be used to improve the soil used in constructing RE buildings. RESHI indicated that a typical addition would be approximately 2%–5% cement. Coal combustion fly ash is not mentioned by Easton, but he indicates that portland cement, asphalt emulsion, and hydrated lime can be used. RESHI indicated that it was familiar with fly ash, but

did not have experience using it. The focus by RE builders is more on identifying the “ideal” soil that requires no amendment for RE construction. They do readily admit that these ideal soils are not typical, and an amendment or modifier is frequently required either to improve the properties of the soil or to increase the strength of the RE walls.

As indicated by the results of the mix design and performance testing performed under this effort, the addition of cement and/or fly ash generally increased the strength of the RE specimens. The fly ash provided the highest improvement in strength when used in conjunction with cement, but even when fly ash was the only amendment used, strengths increased. The Coal Creek Station fly ash used in this study is not a highly cementitious fly ash, so to achieve a prescribed strength for a specific soil, higher additions of fly ash would be required than for cement. The EERC did not evaluate other more cementitious ashes, but based on experience with fly ash in cementitious applications (Pflughoeft-Hassett, 1996; Dockter, 1994a, 1994b, 1997; Moretti, 1993), it can be assumed that additions of any cementitious fly ash would be higher than cement. Noncementitious fly ash (generally from bituminous coal) would not be expected to be useful as an amendment for RE.

This raises the question of the practicality of using fly ash as an amendment for RE construction. While it is technically feasible to use Coal Creek Station fly ash, and likely any cementitious fly ash, to improve the strength of RE walls, EERC results indicate that as much as twice as much ash might be required as compared to cement. This increase in amount might offset the cost differential between cement and fly ash. The EERC generally assumes that fly ash is approximately one-half the cost of cement. The cost of fly ash is variable, based on several factors, including cost of transportation to the use site. Materials for RE construction represent a very limited part of the cost. The primary cost of RE construction is labor. At the very low percentages of addition for either cement or fly ash, any cost saving to the builder is expected to be minimal.

Easton (1996) discusses the addition of bagged cement. According to Mr. Andrew Stewart, En-Rock, Inc., a regional ash marketing company, and Mr. Duane Dumas, Concrete Services, a regional readymix supplier, bagged fly ash is not currently available from sources such as lumberyards or home improvement centers. This availability issue could make the use of fly ash less desirable simply because it may require more investigation or knowledge to obtain fly ash for a RE project. Options to obtain fly ash would include from a local ready-mix supplier or directly from a power plant. Most ready-mix suppliers use fly ash in concrete and, therefore, have a supply of fly ash, but the means of delivery would likely be in a truck, which raises issues of dusting, both in transport and in unloading, and storage at the construction site. Storage of unconstrained fly ash at any construction site is unlikely to be permitted by local and state authorities, and even if it is permitted, the fly ash cannot be exposed to moisture before use, or the cementitious characteristic may be exhausted because of hydration reactions. If fly ash is obtained at a power plant, the same transportation and storage issues apply, and it may be less convenient for the purchaser. In either case, it is likely that the RE construction would be performed during the “construction season,” which may impact the ability to acquire fly ash from either of these sources.

RESHI also discussed the issue of aggregate present in soils or added to the RE mix. It indicated that only up to 1 in. of aggregate could be tolerated in an 18-in. RE wall to maintain the proper adhesion and strength.

Obtaining bottom ash will likely also be less convenient than obtaining aggregate. Bottom ash may be available from an aggregate dealer, a bottom ash marketer, or a power plant. It may be permissible to store bottom ash at a construction site because it is not as fine as fly ash and not susceptible to hydration reactions. In North Dakota, bottom ash is available at very low cost, but transportation may be costly, depending on the distance from the source to the use site. Depending on size requirements (only 1-in. or smaller aggregate is allowable in 18-in. walls), the bottom ash may require separation or crushing so it meets size requirements.

The EERC reviewed confidential information from Jerry Nagel on the proposed North Dakota RE construction project and the RE placement technology developed by Mr. Nagel. The proposed building plan takes into account and addresses rainwater management to minimize exposure of the RE to water. The proprietary equipment that Mr. Nagel has designed for RE placement meets the basic requirements of RE forming materials described by McHenry (1984); the form 1) should have the same width as the foundation, 2) must be stable and/or anchored to allow adequate compaction, and 3) must accommodate 6–8-inch lifts of soil to be placed and compacted to approximately 30–90 psi. The EERC concurs with Mr. Nagel that a demonstration of his placement technique is required to determine that it has commercial potential. The RE building design and placement equipment proposed by Mr. Nagel are independent of the materials, as are any of the RE designs or placement techniques. The primary requirements are that the soil or soil mixture meet certain performance criteria and that any stabilized soils be placed prior to the setting of the soil. The incorporation of bottom ash or fly ash will not require modifications to any of the placement technologies reviewed.

Using regional figures and information from local trucking companies and ready-mix suppliers, estimates of the potential for ash use in RE construction were made. The details of this evaluation are presented in Appendix C. Based on the construction of a moderate-sized home (1500 ft²), the technology proposed by Jerry Nagel, and relatively high additions of fly ash (20%) and bottom ash (30%) in the RE soil mix, it was estimated that approximately 50 tons of fly ash and 70 tons of bottom ash would be used to construct the outer walls of a 30 by 50-ft home with walls 8 ft high and 2.5 ft thick. Based on the number of RE homes built in New Mexico (1994 figures), it was assumed that three RE homes might be built in North Dakota annually, resulting in the utilization of 150 tons of fly ash and 210 tons of bottom ash in this proposed application. Annual production of fly ash in North Dakota is approximately 1.6 million tons, and annual production of bottom ash is approximately 0.9 million tons. It was concluded that the RE application has low potential for North Dakota ash use within North Dakota.

Assumptions and calculations used in evaluating the potential for exportation of North Dakota ash for regional RE construction projects are presented in Appendix C. Although fly ash is transported relatively long distances for use in the concrete market, it is important to note that the fly ash to be used for RE needs only to be cementitious and does not have to meet the same requirements as fly ash used in concrete. It was estimated that transportation costs would be approximately \$1–\$2/mile for a 25-ton load of either fly ash or bottom ash. Based on the cost of

competing materials, cement versus fly ash and sand versus bottom ash, it was determined that fly ash could be shipped a maximum of 500 miles at a competitive price. However, it was also determined that many other power plants producing cementitious fly ash are located within the 500-mile radius of any North Dakota power plant. It was concluded that because of locally available cementitious fly ash in the region, it is unlikely that North Dakota fly ash would be exported for RE construction projects. The transportation cost for bottom ash is the same as for fly ash. In RE construction, bottom ash or sand could be used in an equivalent manner. Sand can be obtained readily throughout the region for an estimated cost of \$9.50/ton. Using this figure, it was estimated that bottom ash could be transported only 200 miles competitively. A 200-mile radius from North Dakota power plants limits the bottom ash use area to portions of South Dakota and Montana. It was also estimated that five RE homes would be built in South Dakota annually, and six RE homes would be built in Montana annually. These 11 homes, if built within the 200-mile radius noted, could use 770 tons of bottom ash. It was concluded that the potential for export of North Dakota ash for RE construction is limited. Combining the potential estimated use of bottom ash in North Dakota and the region for RE construction, less than 0.2% of North Dakota's bottom ash production would be used in this application.

CONCLUSIONS

- Lignite fly ash and bottom ash can be used in limited quantities as amendments to soils for RE construction.
- Bottom ash increased the R-value of a RE specimen and did not significantly change the soil properties of cohesion and unconfined strength for the soil tested. The use of bottom ash must be balanced with the specific soil to be used.
- Cement, cementitious fly ash, and combinations of these materials added to soil provide improved strength. In this study, cement and combined cement and fly ash provided a greater improvement in strength than fly ash, although the greatest strengths were attained through cement addition alone. The use of fly ash alone increased the strength and durability of RE specimens over soil-only specimens, but the fly ash-amended soils did not meet requirements for strength in the New Mexico Adobe and Rammed-Earth Building Code.
- The EERC does not anticipate that RE construction will be widely used in North Dakota because it is not a current construction technique in the geographic region. It is commonly accepted and best suited to climates with warm or moderate temperatures and precipitation. To build a significant number of housing units would require extensive costs associated with training and maintaining a labor force.
- Transportation costs would likely limit the use of North Dakota bottom ash or fly ash to North Dakota and the region, because other cementitious fly ash is available throughout the western United States and cement is available throughout the United States. The builder's choice of additive may also be impacted by delivery and handling options.

- The anticipated rates of addition of bottom ash and fly ash to soil for RE and the low potential for RE construction in the region make this a low-volume application for North Dakota fly ash and bottom ash.

REFERENCES

American Lung Association. *Indoor Air Pollution Fact Sheet*, 1993; 2 p.

Bourgeois, J-L; Pelos, C. *Spectacular Vernacular: The Adobe Tradition*; Aperture Foundation, Inc.: New York, 1989.

Bryggman, T.; Nallick, J. *Use of Coal-Combustion By-Products: Status and Opportunities in Region 8*; Report for U.S. Department of Energy Region 8: Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming; Jan 1993.

Burlington Construction, Inc. www.earthconstruction.com/burlington.htm (accessed 2000).

Dockter, B.A. *Comparison of Dry Scrubber and Class C Fly Ash in CLSM Applications*; Topical Report (July 1, 1993 B June 30, 1994) for Coal Ash Resources Research Consortium Members; EERC Publication 94-EERC-03-5; Energy & Environmental Research Center: Grand Forks, ND, April 1994a.

Dockter, B.A. *High-Volume Fly Ash Concrete in Small Construction Projects*; Topical Report (JanBDec 1993) for University of North Dakota Plant Services; EERC Publication 94-EERC-03-11; Energy & Environmental Research Center: Grand Forks, ND, April 1994b.

Dockter, B.A.; Pflughoeft-Hassett, D.F. Utilization of North Dakota Lignite Combustion By-Products in Road Building Applications. In *Proceedings of the 1997 North Dakota Academy of Science Symposium*; Feb 1997.

Easton, D.R. *The Rammed Earth House*; Chelsea Green Publishing Company: White River Junction, VT, 1996.

Hassett, D.J.; Pflughoeft-Hassett, D.F.; Lillemoen, C.M.; Lucht, J.R. Development of a Technique to Characterize Pozzolanic/Cementitious Materials by Heat of Hydration. Presented at the Pittcon94 Conference. Chicago, IL. Feb 27 – March 4, 1994.

McCarthy, G.J.; Solem, J.K.; Manz, O.E.; Hassett, D.J. *Use of a Database of Chemical, Mineralogical and Physical Properties of North American Fly Ash to Study the Nature of Fly Ash and Its Utilization as a Mineral Admixture in Concrete*; Western Fly Ash Research, Development and Data Center Topical Report; Energy & Environmental Research Center: Grand Forks, ND, Sept 1990.

McHenry, P.G. *Adobe and Rammed Earth Buildings*; University of Arizona Press: Tucson, AZ, 1984.

- Moretti, C.J. *Fly Ash Utilization in McLean County, North Dakota*; Final Technical Progress Report (Oct 1, 1990 B June 30, 1992) for U.S. Department of Energy Contract No. DE-FC21-86MC10637; Energy & Environmental Research Center: Grand Forks, ND, March 1993.
- National Home Builders Association. Results from the Field: Technology Inventory B Rammed Earth Construction. www.nahbrc.org (accessed Aug 2000).
- New Mexico Energy, Minerals, and Natural Resources Department Energy Conservation and Management Division. www.emnrd.state.nm.us (accessed Aug 2000).
- Pflughoeft-Hassett, D.F.; Hassett, D.J.; Dockter, B.A. High-Volume Fly Ash Utilization and the Effects on Groundwater in North Dakota. In *Proceedings of the 10th International Coal Ash Use Symposium*; Orlando, FL., Jan 18–21, 1993.
- Pflughoeft-Hassett, D.F.; Hassett, D.J.; Dockter, B.A.; Eylands, K.E. *The Characterization of Coal Creek Station Fly Ash for Utilization Potential*; Final Report for Cooperative Power; Energy & Environmental Research Center: Grand Forks, ND. Feb 1993.
- Pflughoeft-Hassett, D.F.; Hassett, D.J.; Lillemoen, C.M. Comparative Leaching of Midwestern Coal Fly Ash and Cements. In *Proceedings of the 10th International Coal Ash Use Symposium*; Orlando, FL., Jan 18–21, 1993.
- Pflughoeft-Hassett, D.F.; Dockter, B.A.; Eylands, K.E.; Hassett, D.J. Survey and Demonstration of Utilization Potential of North Dakota Lignite Ash Resources. Final Report for NDIC. EERC No. 96-EERC-04-01, April 1996.
- U.S. Department of Energy Center of Excellence for Sustainable Development. Sustainable Development Resource Database: Rammed Earth Works. www.sustainable.doe.gov (accessed Aug 2000).
- U.S. Environmental Protection Agency, U.S. Department of Health and Human Services and U.S. Public Health Service. *A Citizen's Guide To Radon: The Guide to Protecting Yourself and Your Family from Radon*; U.S. Government Printing Office: Washington, DC, 1994; 12 p.
- Zielinski, R.A.; Budahn, J.R. Radionuclides in Fly Ash and bottom Ash: Improved Characterization Based on Radiography and Low-Energy Gamma Ray Spectrometry. *Fuel*, **1998**, 4, 77, 259–267.
- Western Region Ash Group. Map of Coal-Fired Plants. www.wrashg.org (accessed Aug 2000).

APPENDIX A

NEW MEXICO ADOBE AND RAMMED-EARTH BUILDING CODE

APPENDIX B

SOIL MIX PERFORMANCE CHARTS

APPENDIX C

CALCULATIONS FOR EVALUATION OF NORTH DAKOTA ASH USAGE IN RAMMED-EARTH CONSTRUCTION

Calculations for Evaluation of North Dakota Ash Usage in Rammed-Earth (RE) Construction

Description	Calculation	Explanation
Soil	8 in. compacted = 4 in.	Assume the starting soil mixture will be compacted to half its original volume. Therefore, an 8-in. lift of soil will be compacted to 4. <i>Source: Jerry Nagel's proposed RE construction plan</i>
Home size	$30 \times 50 = 1500 \text{ sq}^2$	Assume a reasonable size rectangular home is $30 \times 50 \text{ ft}$ and RE is used for outside walls only. Average wall thickness is 30 in. and wall height is 8 ft. <i>Source: Jerry Nagel's proposed RE construction plan</i>
Amount of soil mix required	$(30 \times 2) + (50 \times 2) = 160 \text{ linear ft}$ $160 \text{ linear ft} \times 2.5\text{-ft thickness} = 400 \text{ ft}^2$ $400 \text{ ft}^2 \times 8 \text{ ft (height)} = \mathbf{3200 \text{ ft}^3}$	To calculate the amount of compacted soil required, assume a high FA content of 20% and a BA content of 30% in the final RE soil mix.
Amount of ash required	$3200 \text{ ft}^3 \times 2 = 6400 \text{ ft}^3 = \text{amount of uncompacted soil required}$ $6400 \text{ ft}^3 / 27 \text{ ft}^3 / \text{ft}^3 = 237 \text{ yd}^3$ of uncompacted soil needed $237 \times 47.4 \text{ yd}^3 \text{ of FA} = 50 \text{ tons fly ash}$ $237 \times 71.1 \text{ yd}^3 \text{ of BA} = 70 \text{ tons bottom ash}$ $47.4 + 71.1 = 118.5 \text{ yd}^3 \text{ ash total}$	Assume 1 yd ³ of fly ash or bottom ash equals 1 ton of ash.
Number of RE homes to be built	Population NM = 1,685,401 Population ND = 633,666 RE homes in NM = 11 Estimated RE homes in ND = 3	Assume a maximum of three RE homes per year would be expected to be built in North Dakota based on a Web site indicating 11 RE homes were built in New Mexico in 1994 (New Mexico Energy Conservation and Management Division, 2000). The population of New Mexico was 1,685,401 in 1995, and the population of North Dakota in 1999 was 633,666. Using this comparison, it is assumed an equivalent number of RE homes might be built on a per capita basis, resulting in an estimate of 2.6 RE homes per year. For ease of calculation, the number is rounded up to 3.

Ash usage	<p>3 homes × 50 tons fly ash = 150 tons</p> <p>3 homes × 70 tons bottom ash = 210 tons</p>	<p>Assuming 3 RE homes are built in North Dakota, a maximum of 150 tons fly ash and 210 tons of bottom ash could be used annually in this application. Knowing that 1.6 million tons of fly ash and 0.9 million tons of bottom ash are produced in North Dakota annually, it can be concluded that RE will not be a significant market for CCBs.</p> <p><i>Source: Bryggman and Nallick, 1993</i></p>
Potential for exporting CCBs to other states for RE construction	<p>ND fly ash cost = \$5–25 per ton</p> <p>ND bottom ash cost = \$1–2 per ton</p>	<p>Assume it would not be feasible to transport North Dakota fly ash further than 500 miles (the distance from central North Dakota to Minneapolis, Minnesota). Ash is usually sold f.o.b. plant. It can be estimated that North Dakota fly ash prices will range from \$5–25 per ton while North Dakota bottom ash would range from \$1–\$2 per ton.</p> <p><i>Source: Mark Flaagen, En Rock Inc., August 31, 2000</i></p>
Marketing in other states		<p>Using a radius of 500 miles around each North Dakota power plant basically limits us to North Dakota, South Dakota, Minnesota, Montana, Wyoming, Nebraska, and Iowa. Each of these states has at least one coal-fired power plant producing cementitious fly ash within the 500-mile radius. It might be feasible to market North Dakota fly ash into Central South Dakota and Northeastern Montana competitively, depending on the potential market for RE because of the lack of coal-fired power plants in those areas.</p>
Shipping cost (Fly ash)	<p>\$5 per ton fly ash × 25 tons = \$125</p> <p>\$1 per mile × 500 miles = \$500</p> <p>\$500 per 25 tons = \$25 per ton shipping cost</p> <p>\$125 + \$500 / 25 tons = \$25 per ton of fly ash</p>	<p>Assume a full truck of ash is 25 tons. It will cost \$20/ton to ship ash 500 miles which would add significant cost to the price f.o.b. plant. Since it is likely fly ash and bottom ash are available at the power plants with the 500-mile radius at similar prices, it is concluded that there is a low potential for North Dakota fly ash to be exported to the surrounding region for RE construction.</p>
Shipping cost (Bottom ash)	<p>\$1 per ton bottom ash × 25 tons = \$25</p> <p>\$1 per mile × 500 miles = \$200</p> <p>\$200/25 tons = \$8 per ton shipping cost</p> <p>\$25 + \$200/25 tons = \$9 per ton of bottom ash</p>	

**Potential for
exporting bottom
ash**

Population SD = 738,171
Population MT = 880,453

Estimated RE homes SD = 5
Estimated RE homes MT = 6

11 homes × 70 tons = 770 tons bottom ash

Assume bottom ash would be exported to South Dakota and Montana for RE construction. Using the 1998 population figures for these states, it can be estimated five RE homes would be built annually in South Dakota and six in Montana. These 11 homes could utilize 770 tons of North Dakota bottom ash; however, it must be noted these calculations assume that all 11 homes would be located within 200 miles of a North Dakota coal-fired plant, so this estimate is likely high. It can be concluded there is limited potential for export of North Dakota bottom ash for RE construction, but total bottom ash exports estimated equate to <0.1% of the annual North Dakota bottom ash production.

Sand substitution Sand = \$9.50 per ton
Bottom ash (F.O.B.) = \$1 per ton

Assume bottom ash can be marketed in a 200-mile radius from the plant because it's competing with sand in RE applications. The cost of bottom ash is \$1–\$2/ton f.o.b. plant, and shipping costs will be \$1–2/mile. Assume a truckload of ash is 25 tons. At 200 miles from the plant, 1 ton of bottom ash will cost \$9/ton. Bottom ash would be competitive with sand within the 200-mile radius. The distance would potentially support export of North Dakota bottom ash into South Dakota and Montana.

Source: Ed Fellner, Strata Corporation, August 31, 2000

**Cement
substitution**

Cement = \$98 per ton
Fly ash = \$48 per ton

Cement is available throughout the region and could be used as an additive to soil for RE in lower percentages than fly ash (5% cement provides good durability). In Grand Forks, cement costs \$98/ton and fly ash costs \$48/ton.

It can be concluded there is no cost advantage to using fly ash, especially if it needs to be transported.

Source: Ed Fellner, Strata Corporation, August 31, 2000